

AVALANCHE PHOTOCONDUCTIVE SWITCHING*

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Abstract

This paper describes work being done at Lawrence Livermore National Laboratory on the avalanche mode of operation of laser triggered photoconductive switches. We have been able to generate pulses with amplitudes of 2 kV - 35 kV and rise times of 300-500 ps, and with a switching gain (energy of output electrical pulse vs energy of trigger optical pulse) of 10^3 to over 10^5 . Switches with two very different physical configurations and with two different illumination wavelengths (1.06 μm , 890 nm) exhibit very similar behavior. The avalanche switching behavior, therefore, appears to be related to the material parameters rather than the optical wavelength or switch geometry. Considerable further work needs to be done to fully characterize and understand this mode of operation.

Introduction

Laser activated photoconductive switching in semiconductors is a promising technology for high speed, high voltage pulse generation. Solid state switches have many advantages over conventional gas and mechanical switching. These include: very fast switching, low trigger jitter, simple mechanical structure, optical isolation of the trigger, high thermal capacity and thermal conductivity, and flexible geometry allowing fabrication of low inductance structures. Switching speed is limited only by the optical trigger speed. Subnanosecond switching is routinely achieved. Current densities as high as 2×10^6 Amperes/cm² have been reported in GaAs photoconductive switches. This high current density combined with breakdown voltages of over 200 kV/cm imply a very high potential instantaneous switched power.

At Lawrence Livermore National Laboratory we are studying photoconductors as switches for a variety of high peak power, short pulse applications that range from accelerator drivers to microwave generation. This is one of three papers that describe our work on photoconductors (see also "Analysis of the Performance of Gallium Arsenide Photoavalanche Switches," W. T. White et. al., and "Subnanosecond Linear GaAs Photoconductive Switching," R. L. Druce, et. al.). In this report we are concentrating our discussion on the avalanche mode of operation.

The linear photoconductive switch is currently the best way to generate high voltage sub-nanosecond pulses. However, the linear mode of operation has one drawback, because each photon generates only one electron-hole pair, high laser energy is required to generate high power electrical pulses. To reduce laser energy, we are exploring avalanche switching in GaAs. Avalanche operation of photodetectors has been known for many years [1]. It was first described in the context of photoconductors by Williamson, et. al. [2]. While avalanche switching has a much higher potential gain, the energy that can be switched by these devices is currently very small. Pulse generation in the several tens of millijoule energy range is the current state-of-the-art for avalanche switching. Scaling up to the much higher energy levels needed for many applications is not a simple task because of the nonlinear nature of the avalanche multiplication process. Recently researchers at Sandia National Laboratory have reported observation of a similar behavior which they call "lock-on" [3]. Lock on has been observed at a voltage which would correspond to a uniform electric field level that is much too small (4-8 kV/cm) to sustain avalanche multiplication. Because these field levels correspond to the onset of Gunn domains, the Gunn effect may play some role. It is, however, difficult to explain the gain in switching energy observed without some form of

avalanche multiplication. Our lock-on results are presented elsewhere (R. Druce et. al.). For all three modes, our goal is to gain an experimental and theoretical understanding of the physical principles of operation, and to determine the limits of operation in terms of voltage, current, power, and energy.

Figure 1 shows a schematic sketch of the observed electrical behavior when switching in the avalanche mode. Let us consider an avalanche switch connected in a simple circuit driving a resistive load as shown in the figure. If we start at a low voltage so that the electric field across the switch is below approximately 20 kV/cm, the switch operates in the linear mode and a small electrical pulse is generated (Fig. 1 - "linear mode") that approximately follows the time behavior of the optical trigger pulse. As the voltage across the switch is increased, at some electric field value a transition occurs at which the amplitude of the electrical pulse suddenly increases by a factor of 50-100 and the switch appears to stay closed indefinitely (Fig. 1 - "avalanche mode"). This behavior is characteristic of the avalanche mode of operation. We cannot be sure that it is caused by avalanche multiplication, but currently that is the best explanation for this effect.

Switch Fabrication

We have fabricated switches having two different geometric structures. The first is the same as that used for linear photoconductive switching (see R. Druce et. al.). It consists of a rectangular piece of GaAs that is 1x5x20 mm, with contact metal on the 1x20 mm faces. Fig. 2 shows a sketch of the other switch configuration. It consists of a rectangular piece of GaAs with a solid metal electrode on the bottom and a doughnut shaped electrode on the top. These switches are illuminated through the hole in the doughnut electrode. A variety of GaAs thicknesses from 0.25 mm to 0.4 mm and a variety of doughnut electrodes with hole sizes varying from 0.4 mm to 1.2 mm have been tried.

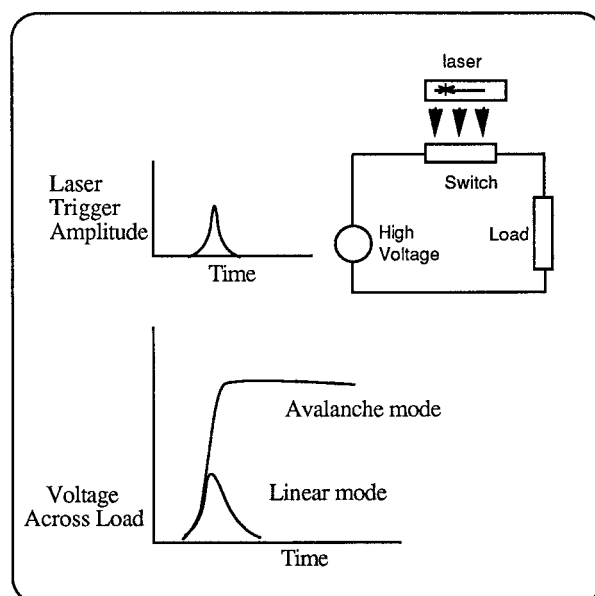


Figure 1: Schematic illustration of observed electrical behavior in the avalanche mode of operation.

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All switches have been fabricated from semi-insulating GaAs that is either LEC grown or Chromium doped to compensate the inherent acceptor concentration. For the doughnut switches, in addition to the

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as-grown GaAs we have also tried creating layers of n- and p-type material near the contacts. N-type material has been created using silicon doping by ion implantation and by MBE growth, and p-type material was created by MBE growth of a Be doped layer. Ion implantation creates a heavily doped layer that is less than 1 μ m thick while the MBE layers were typically a few μ m thick. All contact metal, so far, has been a standard Au-Ge-Ni-Au alloy which is used commonly for GaAs integrated circuits. We plan to use Ti-Pt-Au for p-type contacts in the future.

Experimental Results

Test Configurations

Our experiments have been performed in two different setups. The first, is identical to that used for the linear mode study and is described elsewhere (see R. Druce et. al.). The other consists of a 50 Ω strip line transmission line circuit in which the doughnut switches are mounted in such a way that they can be illuminated through an optical fiber. The latter test circuit is shown schematically in Fig. 3. A typical output pulse attenuated and measured across the 50 Ω load impedance of a high speed transient digitizer (Tektronix 7250) is shown in Fig. 4.

The primary purpose of our experiments is to characterize this mode of behavior in sufficient detail that along with our modeling effort (W. White et. al.) we can develop an understanding of the primary physical mechanisms of switching. Understanding the physics of operation is crucial to the design and development of larger, higher power switches needed for most applications.

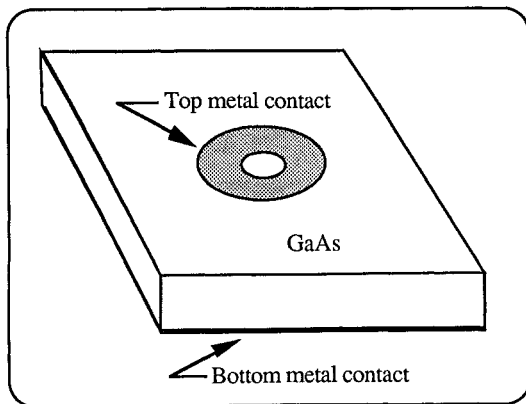


Figure 2: Sketch of "doughnut" electrode configuration used for some of the switch structures

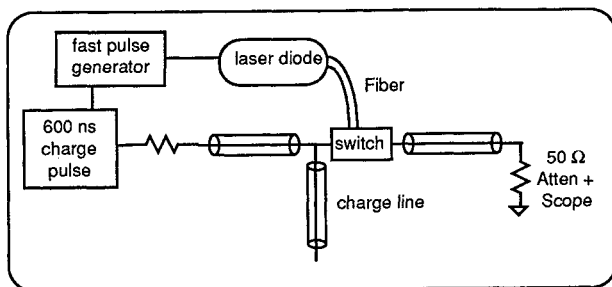


Figure 3: Schematic diagram of test circuit used with doughnut switch

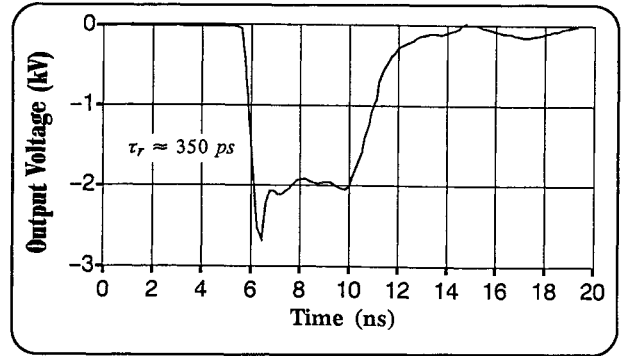


Figure 4: Typical output pulse measured across the 50 Ω load of the circuit in Fig. 3.

A variety of measurements have been made with both experimental setups, and several different structures of the doughnut switches as well as rectangular switches described above. A detailed description of all the measurements is beyond the scope of this report. We, instead, present here a summary of the major trends that we have observed. These measurements are continuing and we are gaining new information on almost a daily basis, but the following is the current status of our experimental results.

Rectangular Switch

Using the rectangular switch geometry with a 5 mm gap between electrodes and the parallel plate transmission line circuit we have been able to generate a 35 kV pulse with a rise time of less than 500 ps. Fig. 5 shows a typical example of such a pulse. The voltage is determined by the electric field that can be held off across the switch. In our case this corresponds to 70 kV/cm and is limited by surface flashover. The pulse length is determined by the transmission line and was about 3 ns in this case. The switching is triggered by a 130 ps optical pulse from a Nd:YAG laser tuned to the 1.06 μ m wavelength. The energy in the electrical pulse is approximately 1000 times the energy in the optical pulse used to trigger the switch. There is a distinct delay between the trigger pulse and the avalanche switching, and a small pre-pulse corresponding to the linear mode of operation before the fast switching occurs can be seen in the figure. The delay decreases with increasing electric field (once the threshold field for the onset of avalanche is exceeded). Jitter was observed, but due to a large jitter in the diagnostic system (750 ps) we are currently unable to determine the contribution of the switch to jitter.

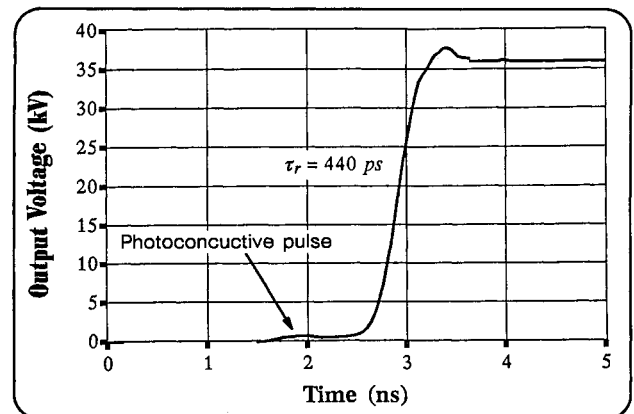


Figure 5: 35 kV pulse generated by avalanche switching of rectangular switch.

Rise Time

Since the optical trigger pulse was significantly faster than the rise time of the electrical pulse, and since we can measure much faster linear mode switching pulses in the same test setup, we assume that the rise time is determined by the physical dynamics of the semiconductor material and not by the trigger or the circuit. One might expect a transit time effect which would imply that rise time would be inversely proportional to the length of the gap. In fact the rise time of the doughnut switches which have an order of magnitude smaller gap is not an order of magnitude faster (see Fig. 4). The shortest rise time we have measured with the doughnut switches has been approximately 350 ps. We are not certain, however, if this longer than expected rise time is due to the material or the circuit, as only slightly faster linear mode pulses (250 ps) were observed in this test circuit. Also, as can be seen in Fig. 4, there is a significant overshoot on the leading edge of the pulse.

Doughnut Switch

Using the doughnut switches we have generated a maximum pulse of 2.5 kV amplitude into a $50\ \Omega$ load with a pulse length of approximately 80 ns. Since the output pulse amplitude is approximately 1/2 the charge pulse voltage, this corresponds to a 5 kV charge pulse. The experiment was done with a gap length of 0.4 mm, corresponding to a hold off field of 125 kV/cm. The energy in the pulse is approximately 10 mJ. The energy in the optical pulse necessary to trigger is as low as 20 nJ, resulting in a gain of approximately 5×10^5 . We observed almost identical switching waveforms using two very different optical triggers. One is a 890 nm laser diode with a 5 ns pulse length, and the other is the 1.06 μm Nd:YAG laser with a 130 ps pulse length. This result surprised us. It implies that the optical wavelength does not significantly affect the switching process.

Another feature of this mode of operation is that there is a threshold field for the onset of the avalanche mode which ranges from about 20 kV/cm to about 60 kV/cm. We have observed similar behavior in all switches including the various doughnut configurations as well as the rectangular switches. To compare switches with varying gap lengths and therefore output voltages, it is useful to normalize the output voltage. When making such normalizations we simply divide by the maximum value in a given set of measurements. Fig. 6 is a typical plot of experimental and theoretical normalized output voltage vs the electric field across the switch before illumination (assuming uniform field distribution). It clearly shows the transition from linear mode to avalanche mode. The 20-60 kV/cm value is considerably lower than the theoretical avalanche breakdown field of ≈ 200 kV/cm. Since avalanche multiplication is exponentially related to the electric field, it is difficult to explain the sudden change of state at 20-60 kV/cm. There are a number of possible explanations for this unusual behavior. They include non-uniform field distribution, two dimensional field enhancement, and field dependent trapping (see W. White et. al.). We are conducting a combined experimental and theoretical study to gain an understanding of this behavior. Understanding this behavior is the key to being able to develop new, higher power switch structures. However, we do not yet have a satisfactory explanation.

Reliability

Device life is another important area for future study. Currently we find that most of the switches fail to hold off the charge voltage after several thousand switching operations. We would like to extend this operational life to several million operations. Again, there are a number of possible effects that could be causing device failure. These include metal migration from the contacts, defects in the GaAs, non-uniform (filamentary) current flow, and thermal effects. We are beginning a systematic study of each of the possible mechanisms to determine which are dominant and to develop fabrication techniques to improve device life.

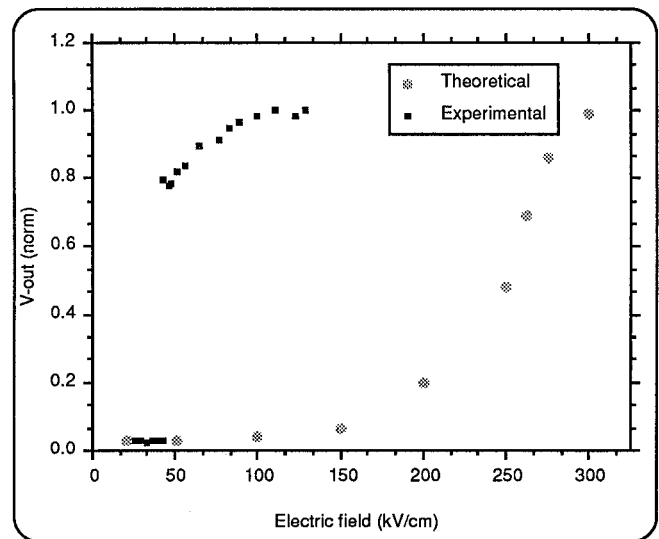


Figure 6: Typical plot of normalized output voltage vs open state electric field for a doughnut switch (using uniform field approximation).

Conclusions

We have described an experimental study of the avalanche mode of operation of laser triggered GaAs photoconductive switches. A number of switches have been fabricated using two different geometries (rectangular and doughnut), and tested in two different experimental circuits. Switch rise times of approximately 350-500 ps have been measured and appear to be independent of laser wavelength or trigger speeds. Pulses with amplitudes of 2.5 kV to 35 kV have been generated. The maximum voltage, so far, appears to be limited only by the maximum electric field that can be held off across the gap of the switch, which in turn appears to be limited by surface flashover. There appears to be a threshold electric field of 20-60 kV/cm necessary for the avalanche mode. We are currently unable to explain this low threshold field value, but research is continuing in this area. We are also continuing research to improve reliability, increase speed, and study alternate geometries and materials such as Indium Phosphide.

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